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EXPERIMENTAL EVALUATION OF A VOLTAGE REGULATOR-EXCITER FOR A 15 KILOVOLT-AMPERE BRAYTON CYCLE ALTERNATOR

by Gary Bollenbacher, Richard A. Edkin, and Dennis A. Perz

Lewis Research Center
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ABSTRACT

A voltage regulator-exciter for a 15 kVA, 120/208 volts, 400 hertz alternator was experimentally evaluated. Emphasis was placed on the effect of the voltage regulator-exciter on the alternator performance. Specific items tested include the voltage regulator-exciter output capacity, its regulating capability, its effect on alternator waveshape, and its performance during transient and startup conditions.

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SUMMARY

Experimental results on a breadboard voltage regulator-exciter for a 15 kilovolt-ampere, 400 hertz Brayton cycle alternator are presented and evaluated. The effect of the voltage regulator-exciter on the alternator performance is assessed by comparing the test results with data for the alternator alone. The following specific areas were tested: voltage regulator-exciter output capacity as determined from the open-loop characteristics, voltage regulation, waveshape effects, power losses, voltage transients resulting from step load changes, and voltage build-up relying on residual magnetism. The test data confirm that the voltage regulator-exciter is well matched to the Brayton cycle alternator and that it meets all design objectives in those areas tested. It was found that at rated output, the efficiency of the alternator-regulator combination is 90.9 percent, which is 0.6 percent less than the efficiency of the alternator alone. The voltage regulation was shown to be less than 0.2 percent. It was further demonstrated that the voltage regulator-exciter produced no detrimental effects on the alternator voltage waveshape and that for ground testing, voltage build-up could be achieved consistently by relying only on the rotor residual magnetism.

INTRODUCTION

A Brayton cycle space power system, presently being investigated at the Lewis Research Center, will convert solar or radioisotope energy into electrical energy. The system is designed to provide 10 kilowatts of electric power at 400 hertz, 120/208 volts. The thermodynamic aspects of this Brayton system are discussed in references 1 to 3. The major electric components of the system are the alternator, the voltage regulator-exciter, the speed control (ref. 4), and the parsitic load banks. Only the first two are discussed in this report.

Prior to the Brayton cycle work, performance of the electrical components for the 35 kilowatt SNAP-8 system was investigated. The experience gained in the SNAP-8 program contributed significantly to the effectiveness of the Brayton cycle program. Unique design changes and refinements for the Brayton system alternator include laminated pole tips and a novel slot insulation system. The principal difference in the Brayton voltage regulator-exciter (VRE), compared to the SNAP-8 VRE, is the use of a transistorized amplification stage.

The objectives of tests performed on the Brayton voltage regulator-exciter and alternator are (1) to evaluate experimentally the transient and steady-state performance characteristics of the alternator and voltage regulator-exciter at design and off-design conditions; (2) to assess the effect of the voltage regulator-exciter on the alternator voltage waveshape; and (3) to determine regulator losses and their effect on alternator efficiency.

Alternator data are included, in part, to allow an evaluation of the effects the VRE has on the alternator performance, and because in some instances meaningful VRE data could be obtained only by testing it with the 400 hertz Brayton cycle alternator.

The program was conducted with a breadboard voltage regulator-exciter and an alternator, which is an electromagnetic and thermal equivalent of the alternator in the turboalternator assembly. Therefore, the data and performance obtained may be utilized directly by a system or spacecraft designer.

DESCRIPTION OF BRAYTON CYCLE ALTERNATOR AND VOLTAGE REGULATOR-EXCITER

The major components of the 400 hertz Brayton cycle electrical system are shown in figure 1. Additional electrical system components, not shown in the figure, are startup and shutdown controls and protection circuitry. The specifications to which the electrical system was designed are listed in table I.

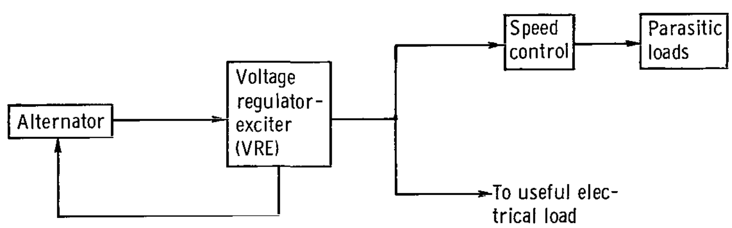


Figure 1. - Brayton cycle electrical system block diagram.

TABLE I. - BRAYTON CYCLE SYSTEM SPECIFICATIONS

APPLICABLE TO ALTERNATOR AND

VOLTAGE REGULATOR-EXCITER

400 Hz Brayton system rating, kW	10
Alternator rating, kW	12
Frequency, Hz	400
Turboalternator speed, rpm	12 000
Phases	3
Voltage, V	120/208
Current, A	41.7
Kilovolt-amperes (apparent power), kVA	15
Power factor	0.8, lagging
Harmonic distortion (line-to-neutral voltage, linear alternator load)	
Any one harmonic, percent	≤3
Total harmonic distortion at 1.0 power factor, percent	≤7
Modulation (amplitude) at rated load, percent	≤1
Crest factor at rated load (measured line-to-neutral)	1.414±10%
Voltage regulation (zero to 100-percent load change), percent	±1
Voltage recovery time from transients (to within 5 percent of rated voltage), sec	1/4
Maximum voltage transient on removal of 1.0 per unit load, percent of rated volts	136.4

Alternator

The homopolar inductor alternator is a three-phase, four-pole, 400 hertz machine. Its continuous rating is 15 kVA at 0.8 lagging power factor and 120/208 volts. It has a stationary field winding located between two stator stacks. The rotor is of solid construction except for the laminated pole tips (to minimize pole-face losses) and the damper windings, which are inserted into the pole tips. The pole tips are electron-beam welded to the main pole body. References 5 and 6 describe the alternator design and performance in more detail.

Voltage Regulator-Exciter

The VRE (ref. 5) must perform two main functions: (1) transform and rectify part of the alternator output to supply alternator field excitation; and (2) regulate the alternator voltage by controlling the alternator field current. While meeting these two basic requirements, the VRE must not adversely affect voltage waveshape or unduly reduce alternator efficiency; during voltage transients, the VRE must respond rapidly but without causing sustained oscillations.

To meet the performance requirements outlined above, the VRE includes two subcircuits: the static exciter and the voltage regulator. The static exciter is of fundamental importance mainly to the performance of function (1). The voltage regulator, by exercising control over the static exciter, is responsible for function (2).

To clarify the following description of the static exciter and voltage regulator, the VRE block diagram is shown in figure 2. For additional information, the VRE schematic diagram and a photograph of the unit tested are given in figures 3 and 4, respectively.

Static exciter. - The static exciter derives its operating characteristics primarily from the saturable current potential transformer (SCPT). Its other components are the linear reactors and the three-phase, full-wave rectifier.

The SCPT (ref. 7) is a three-phase magnetic device. Each phase has two primary windings, called current and potential windings, and one secondary or output winding. An additional control winding is common to all three phases.

With the alternator at no load and rated voltage, feedback through the potential winding supplies the alternator's excitation requirement. When the alternator is under load, additional feedback from the SCPT current winding supplies the increase in excitation requirement. The linear reactors in series with each potential winding compensate the SCPT output for changes in load power factor. The effect of current in the SCPT control winding is to drive the magnetic material of the SCPT into saturation, thereby reducing the SCPT output.

To operate properly, the static exciter must be designed to produce higher than rated alternator voltage when the SCPT control current is zero. The voltage regulator must then supply control current to reduce the alternator voltage to rated value.

Voltage regulator. - The voltage regulator is that part of the VRE that supplies control current to the static exciter. It consists of a voltage sensing circuit, a voltage ref-

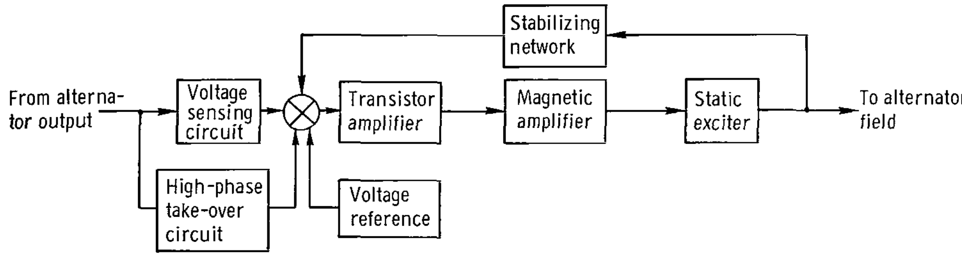


Figure 2. - Block diagram of voltage regulator-exciter.

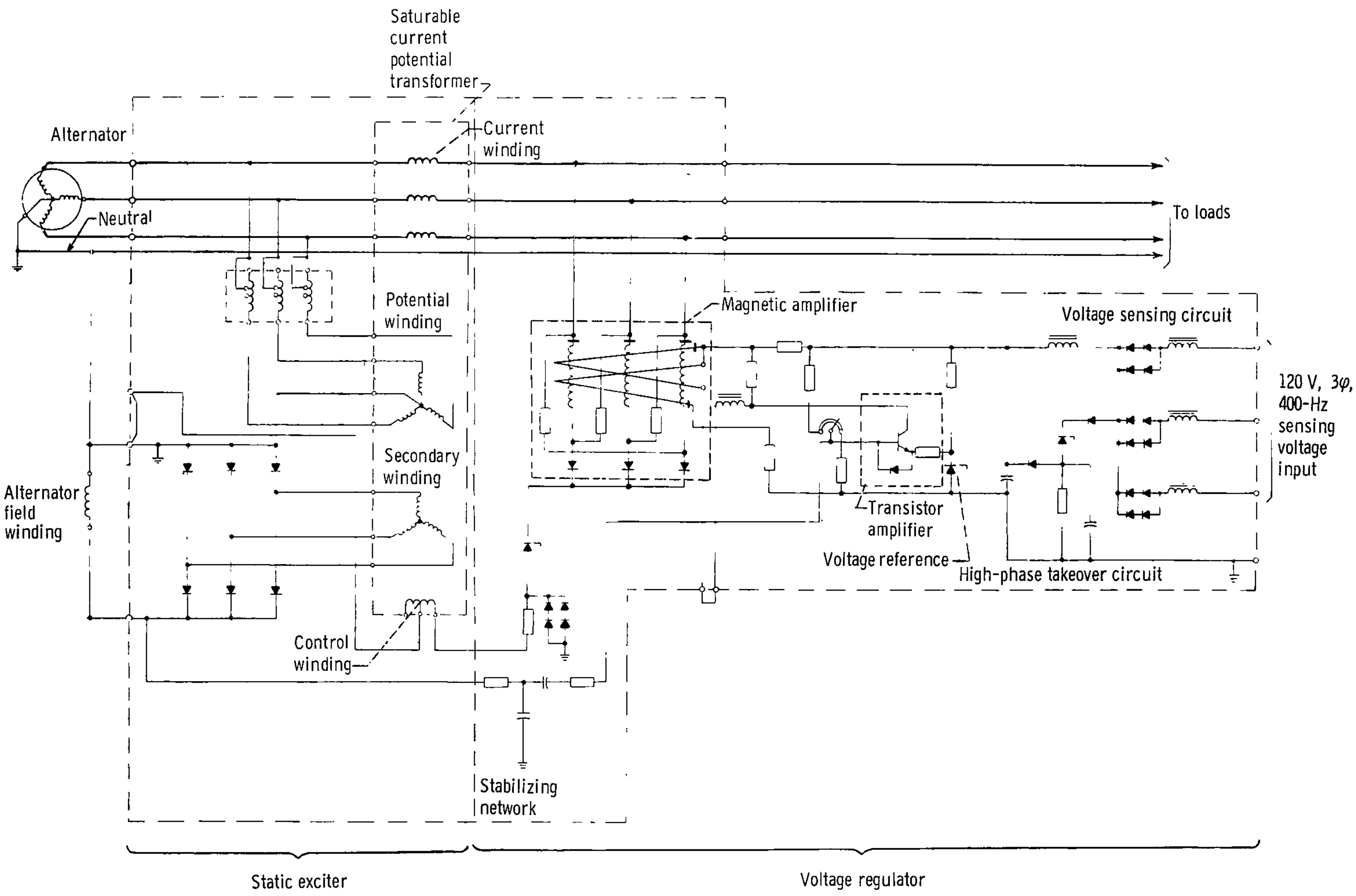


Figure 3. - Schematic diagram of voltage regulator-exciter.

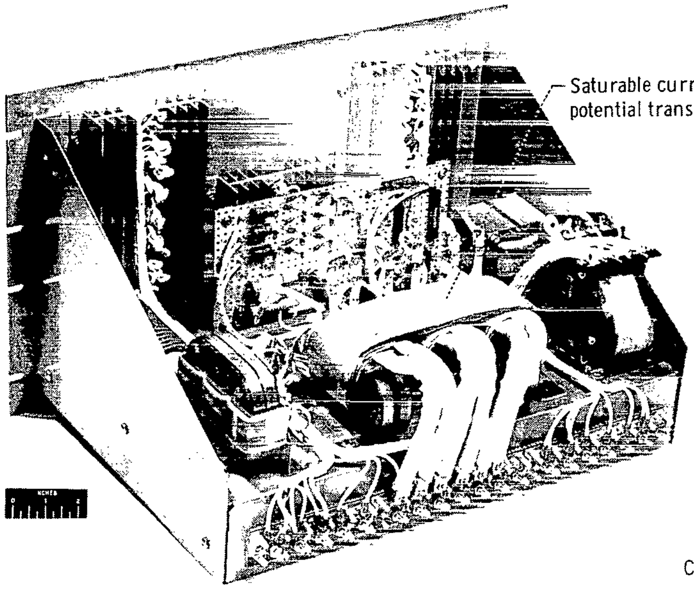


Figure 4. - Voltage regulator-exciter.

erence, a comparison circuit, a transistor amplifier, a magnetic amplifier, a high-phase takeover circuit, and a stabilizing network (fig. 3).

The voltage-sensing circuit provides a direct current signal obtained by half-wave rectification and filtering of the alternator output voltage. This signal is approximately proportional to the average of the three line-to-neutral root-mean-square voltages. The signal is compared with the voltage reference, and the difference or error signal is then amplified in two successive stages. The current output of the second amplification stage is applied to the SCPT control winding.

The regulator is designed in such a manner that if the phase voltage is higher than 120 volts, the SCPT control current will increase. The effect of increased control current is to lower the excitation and thereby reduce the alternator phase voltage. If the phase voltage is less than 120 volts, the reverse happens.

The stabilizing network provides negative feedback from the field terminals to the transistor amplifier. Its purpose is to minimize voltage oscillations during transients induced by load switching. The high-phase takeover circuit limits the maximum voltage on any one phase during severely unbalanced loads.

RESULTS AND DISCUSSION

The material presented in this report has been organized into five sections. Each section includes a description of the test method used if it was unusual or if it differed appreciably from MIL STD 705 A. The test facility and instrumentation are described in detail in reference 6.

All test data are for three-phase balanced load conditions and, except for the last section (Voltage Buildup), for 400 hertz. All references to alternator load, voltage, or current are given in the per unit system as follows:

1 per unit load	= 12 kW
1 per unit phase voltage (line-to-neutral)	= 120 V
1 per unit line current	= 41.7 A

Rated load refers to 12 kW, 0.8 pf lagging (table I). All alternator voltages are measured line-to-neutral; all power factors except unity are lagging.

Basic Voltage Regulator-Exciter Functions

VRE open-loop characteristics. - The VRE open-loop characteristics show, when compared to the alternator constant impedance saturation curves, how well the VRE performs one of its basic functions: supplying field current to the alternator.

To define the VRE open-loop characteristics and the alternator constant impedance saturation curves and to interpret these curves properly requires an understanding of figure 5. The figure is a simplified block diagram of the experimental set-up used to obtain the two families of curves. It shows the alternator supplying power to a fixed impedance load through the SCPT current windings of the VRE. The alternator is excited, not by

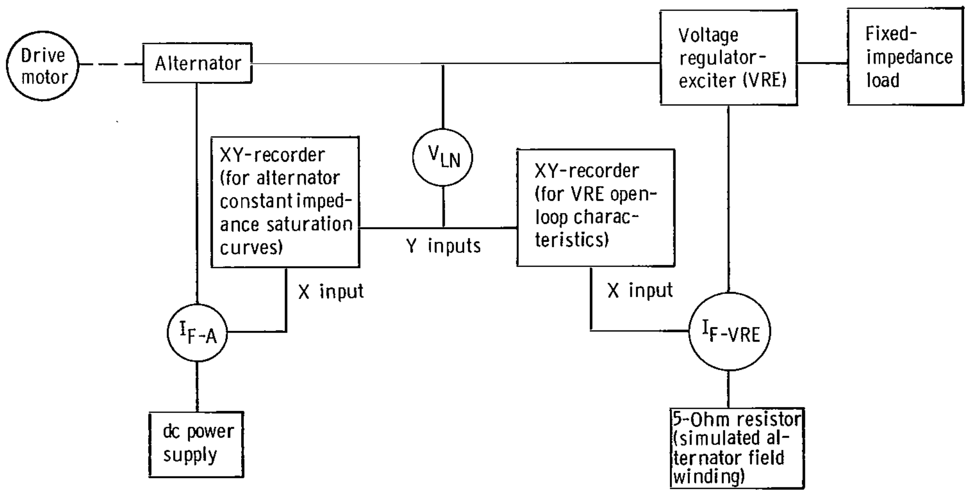


Figure 5. - Test setup to obtain voltage regulator-exciter open-loop characteristics and alternator constant impedance saturation curves. (See table II for values of load impedance used.)

the VRE, but with a regulated direct current power supply. The VRE output is fed to a fixed resistor. For this test the resistor is an adequate simulation of the alternator field winding since only steady-state measurements are involved. The alternator phase voltage V_{LN}, adjusted by controlling the alternator field current I_{F-A}, causes VRE output current I_{F-VRE} to flow through the simulated field winding.

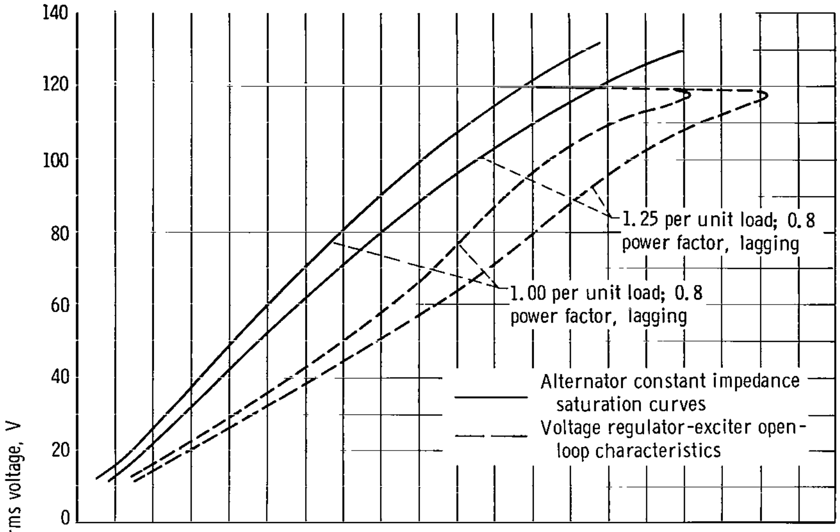
The VRE open-loop characteristics are a family of curves of V_{LN} against I_{F-VRE} with alternator load impedance as a parameter. For values of V_{LN} less than 120 volts, they give the maximum field current the VRE can supply for a given alternator load impedance and line-to-neutral voltage. Similarly, the alternator constant impedance saturation curves are plots of V_{LN} against I_{F-A}. They show, for various values of load impedance, how much field current is required by the alternator at any given voltage.

The open-loop characteristics are also dependent on the value of field resistance. However, throughout this test, only one value, 5 ohms, was used. This is the hot alternator field resistance (ref. 6) and is the highest value expected. Its use led to conservative results since lowering the field resistance increases I_{F-VRE}.

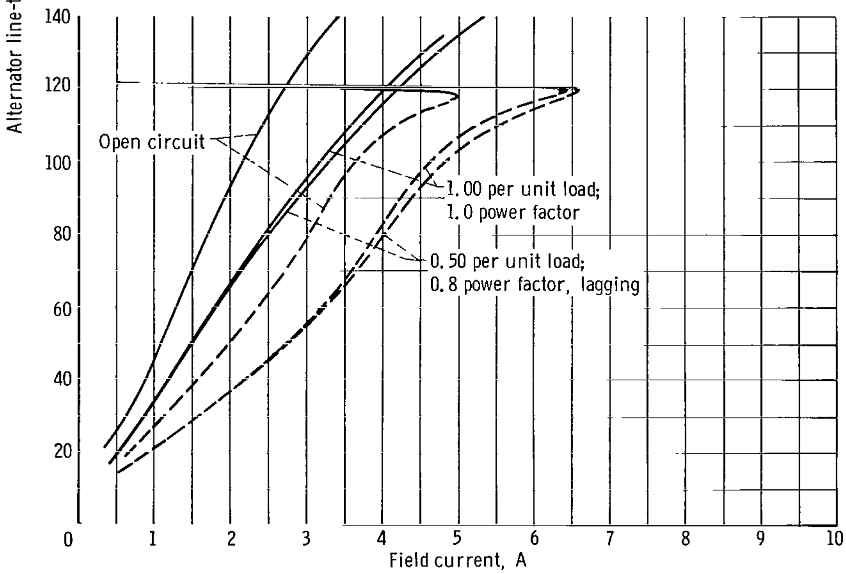
The use of two XY-recorders, as shown in figure 5, gave both the open-loop characteristics and the constant impedance saturation curves. A set of curves was obtained for each value of load impedance shown in table II. The table also lists for each impedance the corresponding alternator load at 120 volts.

TABLE II. - LOAD IMPEDANCE FOR WHICH VOLTAGE REGULATOR-EXCITER OPEN-LOOP CHARACTERISTICS WERE OBTAINED AND CORRESPONDING LOAD AT 120 V, 400 Hz

Load impedance at 400 Hz		Load power at 400 Hz 120 V line-to-neutral		
Magnitude, ohms	Phase angle, deg	Percent of rated power	Power per phase, kW	Power factor
7.20	0	50	2	1.0
5.75	36.8	50	2	0.8, lagging
3.60	0	100	4	1.0
2.88	36.8	100	4	0.8, lagging
2.30	36.8	125	5	0.8, lagging
∞	-	0	0	-



(a) Per unit loads, 1.25 and 1.00; power factor, 0.8 (lagging).



(b) Per unit loads, 0, 1.00 (power factor, 1.0), and 0.50 (power factor, 0.8 (lagging)).

Figure 6. - Voltage regulator-exciter open-loop characteristics and alternator constant impedance saturation curves. Loads given at rated voltage.

To facilitate comparison (even though it entailed plotting the dependent variables I_{F-VRE} along the X-axis) all VRE open-loop characteristics and alternator constant-impedance saturation curves for 1.0 and 1.25 per unit load, 0.8 power factor (lagging), have been combined in figure 6(a). The remaining curves are shown in figure 6(b).

The data show that at open circuit and rated voltage (±1 percent) the alternator requires 2.75 amperes field current while the VRE is capable of supplying 4.75 amperes. Expressed in percent, this gives an output capacity of

$$\frac{4.75}{2.75} \times 100 \approx 173 \text{ percent}$$

Similarly, at rated load the VRE output capacity is 133 percent.

Voltage regulation with the VRE. - Voltage regulation is the second basic VRE function. It is defined as the percentage change in alternator voltage, after a transient period, resulting from a 1-per unit change in alternator load. Stated as an equation

$$\text{Voltage regulation (\%)} = \frac{\Delta V_{LN}}{\text{Rated load design voltage}} \times 100$$

$$= \frac{\Delta V_{LN}}{120} \times 100$$

where ΔV_{LN} = no load voltage - rated load voltage.

To determine the voltage regulation, the alternator voltage on each phase was meas-

TABLE III. - VOLTAGE

REGULATION TEST RESULTS

Phase	Average voltage change, ΔV_{LN}, V	Voltage regulation, percent
A	0.22	0.183
B	.22	.183
C	.25	.208
Average		+0.191

ured both before and after load application using a true root-mean-square, null-type digital voltmeter having a $\pm\frac{1}{4}$-percent accuracy from 100 hertz to 10 kilohertz. Several sets of data were obtained and averaged. As shown in table III, the average regulation for the three phases is less than +0.2 percent, which is well within the ±1.0 percent design goal.

Voltage Regulator-Exciter Effect on Alternator Efficiency

The alternator losses and efficiency without the VRE are presented in reference 6. The VRE losses and their effect on the alternator efficiency are evaluated below.

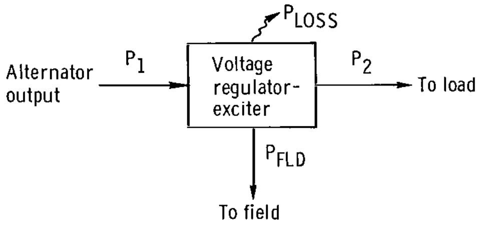


Figure 7. - Power balance of voltage regulator-exciter.

Consider the VRE as shown in figure 7. P_1 is the total power supplied by the alternator, and P_2 is the total power delivered to the load. Their difference $(P_1 - P_2)$ is the power absorbed by the VRE. Part of the absorbed power goes into field excitation; the rest constitutes the VRE losses. Expressed in equation form

$$P_1 - P_2 = P_{FLD} + P_{LOSS}$$

or

$$P_{LOSS} = (P_1 - P_2) - P_{FLD}$$

P_1 and P_2 (at rated load) are both approximately 12 000 watts while their difference is only 200 to 300 watts. If P_1 and P_2 are measured separately, the accuracy of the measurements has to be nearly 0.06 percent to obtain the difference to an accuracy of 5 percent. Instead, a unique method was devised to obtain the quantity $P_1 - P_2$. The method, explained in detail in the appendix, requires the measurement of two quantities P_A and P_B. Both have the units of watts and are defined by the following equations:

$$P_A = (V_1 - V_2)(I_1)\cos\theta_A$$

$$P_B = (I_1 - I_2)(V_2)\cos\theta_B$$

where

V_1 line-to-neutral alternator output voltage

V_2 line-to-neutral load voltage

I_1 alternator output current

I_2 load current

θ_A phase angle between $(V_1 - V_2)$ and I_1

θ_B phase angle between $(I_1 - I_2)$ and V_2

Assuming three-phase balanced loads and voltages, the desired quantity $P_1 - P_2$ is then given by

$$P_1 - P_2 = 3(P_A + P_B)$$

The factor 3 is needed since P_1 and P_2 are total power while P_A and P_B are defined on a per-phase basis.

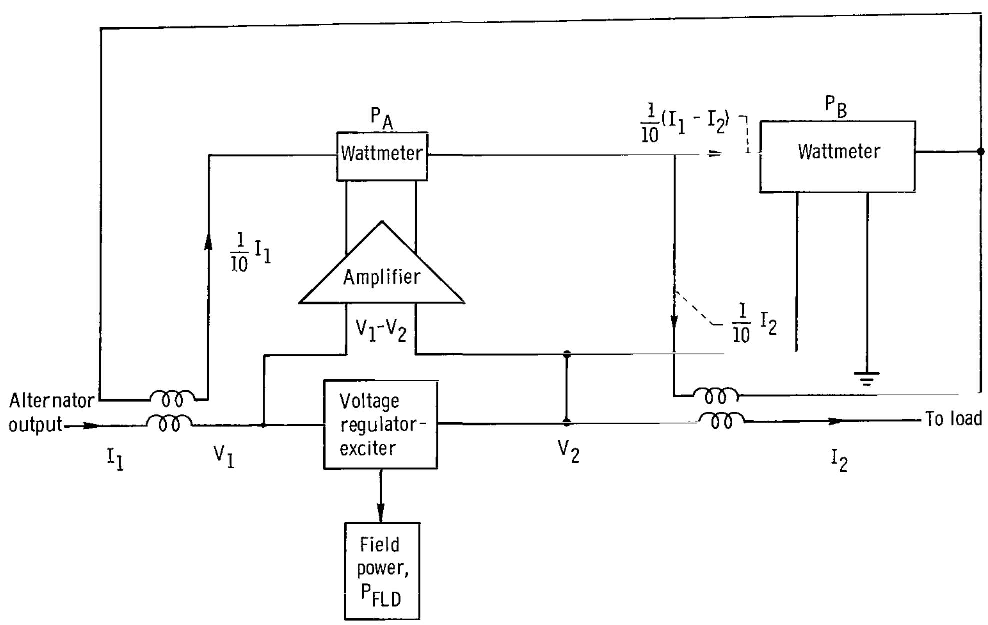


Figure 8. - Test setup for measuring voltage regulator-exciter power loss.

TABLE IV. - VOLTAGE REGULATOR-EXCITER LOSSES AND EFFICIENCY

Alternator load		Experimental data			Calculated from experimental data		
Power factor (lagging)	Load, kW	P_A, W	P_B, W	Field excitation power, P_{FLD}, W	Power absorbed, $P_1 - P_2$, W	VRE power losses, P_{LOSS}, W	Efficiency, η_{VRE}, percent
---	0	0.40	29.5	25.3	89.7	64.4	28.2
0.8	3	8.0	28.0	43.2	108.0	64.8	40.0
	6	19.0	27.5	69.4	139.5	70.1	49.7
	9	33.9	26.5	105.0	181.2	76.2	57.9
	12	50.8	23.0	140.0	221.4	81.4	63.2
	15	75.0	25.5	205.0	301.5	96.5	68.0
0.9	3	7.2	28.0	38.9	105.6	66.7	36.8
	6	16.2	24.5	57.0	122.1	65.1	46.7
	9	27.0	21.0	77.8	144.0	66.2	54.0
	12	41.3	16.0	105.9	171.9	66.0	61.6
	15	60.1	14.0	151.0	222.3	71.3	67.9
0.95	3	6.5	26.5	34.5	99.0	64.5	34.8
	6	14.3	22.2	47.0	109.5	62.5	42.9
	9	25.1	18.5	69.2	130.8	61.6	52.9
	12	35.9	12.5	85.1	145.2	60.1	58.6
	15	51.4	8.5	117.0	179.7	62.7	65.1
1.0	3	5.4	24.0	28.3	88.2	59.9	32.1
	6	11.6	18.0	35.6	88.8	53.2	40.1
	9	19.2	12.5	44.5	95.1	50.6	46.8
	12	29.1	7.0	60.0	108.3	48.3	55.4
	15	41.0	1.0	79.0	126.0	47.0	62.7

P_A and P_B are both small, typically from 10 to 50 watts. Experimentally, the technique was implemented as illustrated in figure 8.

The data obtained (table IV) consisted of values of P_A, P_B, and P_{FLD} for various alternator loads. From these values $P_1 - P_2$, P_{LOSS}, and the voltage regulator-exciter efficiency η_{VRE} were calculated. The VRE efficiency η_{VRE} is defined as

$$\eta_{VRE}(\%) = \frac{P_{FLD}}{P_{FLD} + P_{LOSS}} \times 100$$

The results of these calculations are shown in the last three columns of table IV and are

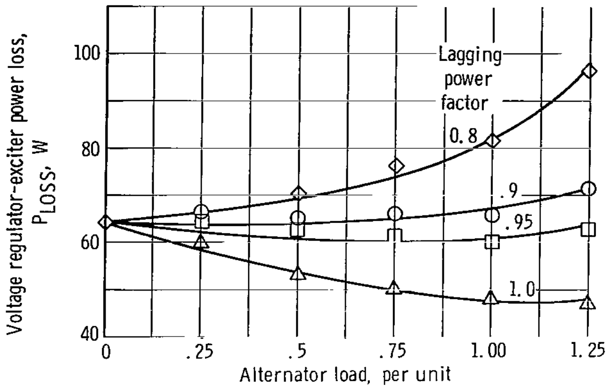


Figure 9. - Variation of voltage regulator-exciter losses with alternator load.

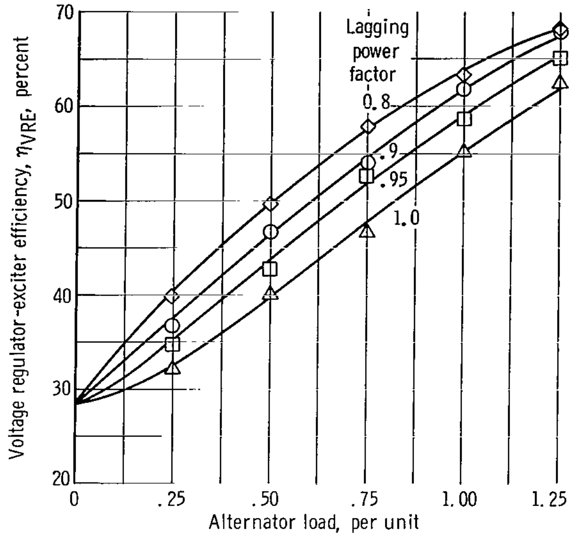


Figure 10. - Variation of voltage regulator-exciter efficiency with alternator load.

plotted in figures 9 and 10. As the figures show, at rated load the VRE power loss is 81.4 watts, and the VRE efficiency is 63.2 percent. At rated power factor and higher than rated load, the VRE losses increase very rapidly, causing the VRE efficiency to show a marked tendency to level off.

Reference 6 gives the efficiency of the alternator as a function of load. How this efficiency is affected by the addition of the VRE can be seen from the following equation:

$$\eta_{A+VRE} = \frac{\frac{\eta_A}{100} P_{LOAD}}{P_{LOAD} + \frac{\eta_A}{100} P_{LOSS}} \times 100$$

where

η_{A+VRE} efficiency of alternator and VRE combination at rated alternator load, percent

η_A efficiency of alternator without the VRE at rated alternator load, percent

P_{OUT} alternator load, W

P_{LOSS} power loss in the VRE, W

Figure 11 shows both efficiencies as a function of alternator load and power factor.

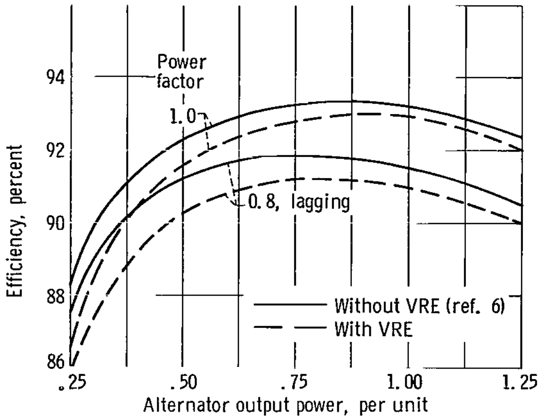


Figure 11. - Comparison of alternator efficiency with and without voltage regulator-exciter. Inlet coolant temperature, 93.4° C; coolant flow rate, 1.66 gallons per minute (0.00625 m^3/min); bearing losses not included.

At rated load the VRE reduces the alternator efficiency from 91.5 to 90.9 percent, a reduction of 0.6 percent.

Voltage Regulator-Exciter Effect on Alternator Voltage Waveshape

To determine what, if any, adverse effects the VRE has on the waveshape of the alternator output voltage, the total harmonic distortion and crest factor were measured and compared with similar data for the alternator alone. In addition, the effect of the VRE on the envelope of the alternator output was obtained by measuring the amplitude modulation. Without the VRE (for constant rotor speed), the amplitude modulation is, of course, zero.

Total harmonic distortion. - Total harmonic distortion (THD) is defined as

$$\text{THD (\%)} = \sqrt{\sum_{i=2}^{\infty} V_i^2}$$

where V_i is the amplitude of the i^{th} harmonic expressed as a percent of the fundamental. For a pure sine wave %THD = 0.

Experimentally, the THD was measured using a wave analyzer which gave the amplitude of each harmonic relative to the fundamental. All harmonics up to the 41st (16 400 Hz), which includes the Brayton alternator slot harmonics (23rd and 25th), were measured. Harmonics higher than the 41st become progressively smaller, and their contribution to the total harmonic distortion was assumed negligible. Thus, the equation for calculating the THD simplifies to

$$\mathrm{THD}\ (\%) = \sqrt{\sum_{i=3}^{41} V_i^2} \qquad (i\ \text{odd})$$

The index i is restricted to odd integers since all even harmonics are zero. This was expected from the waveshape symmetry and confirmed by the data.

TABLE V. - EFFECT OF VRE ON TOTAL HARMONIC DISTORTION

Alternator load		Total harmonic distortion		Change in total harmonic distortion, ΔTHD, percent (b)
Magnitude,	Power factor	Without VRE (a)	With VRE	
0	---	6.597	6.904	-4.65
1	1.0	2.722	2.721	.036
1	.8	2.674	2.630	1.65

[a]Values were obtained from ref. 6.

[b]Percent ΔTHD $\equiv \left[\dfrac{\mathrm{THD}_{\text{without VRE}} - \mathrm{THD}_{\text{with VRE}}}{\mathrm{THD}_{\text{without VRE}}}\right] \times 100.$

The results of the THD measurements with the VRE are shown in table V for several different loads. Also shown are the results of similar measurements without the VRE, as reported in reference 6. The last column shows the percent change in the THD when the VRE is added. It is quite apparent from this last column that the effect of the VRE on the voltage waveshape is insignificant.

Crest factor. - The crest factor is the ratio of peak to root-mean-square voltage. For a sine wave, the crest factor is $\sqrt{2}$; for a square wave it equals 1.0, and for a triangular wave $\sqrt{3}$. If the THD is small, as was previously shown, then it may be stated that a waveform whose crest factor is less than $\sqrt{2}$ is a "flattened sine wave" while one whose crest factor is greater than $\sqrt{2}$ is a "pointed sine wave."

The crest factor of the line-to-neutral waveform was measured for a number of alternator loads both with and without the VRE. The meter used allowed measurement of both peak and true root-mean-square voltage of the waveshape. Prior to its use, the meter was calibrated against a sine wave of known quality (THD < 0.25 percent) to give a ratio of peak to root-mean-square reading of $\sqrt{2}$. From the individual peak and root-mean-square readings, crest factor was then readily calculated.

The results of these measurements are plotted in figure 12. The figure shows a definite trend: with the VRE the crest factor is consistently lower than without the VRE,

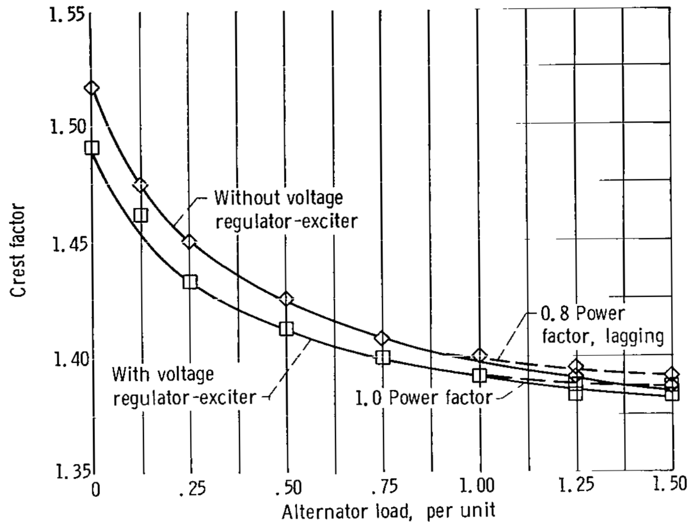


Figure 12. - Effect of voltage regulator-exciter on crest factor.

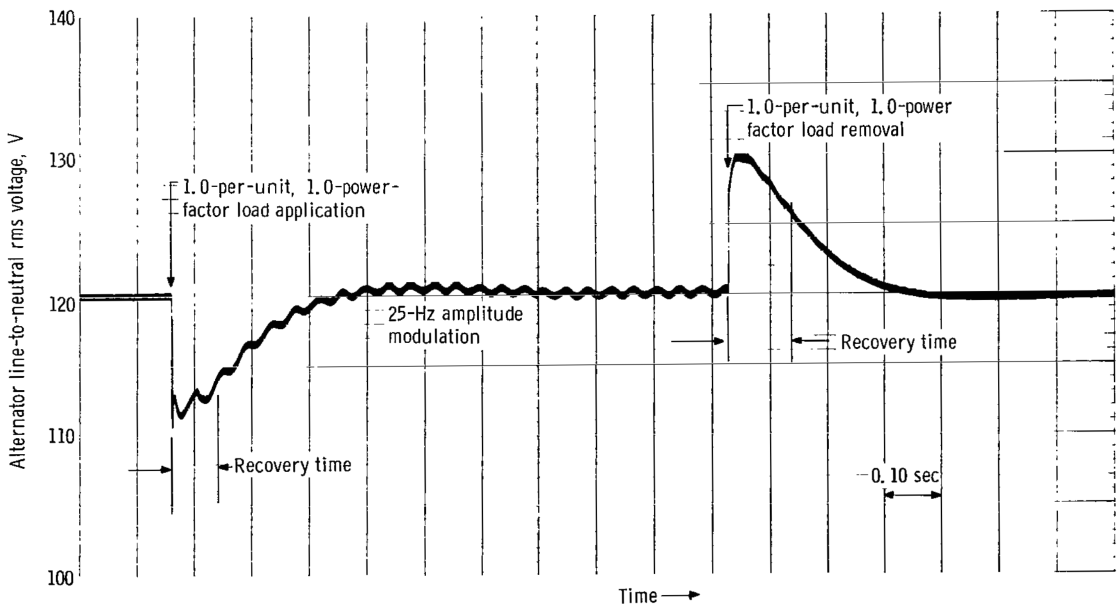


Figure 13. - Voltage transients due to 1.0-per-unit, 1.0-power-factor load application and removal.

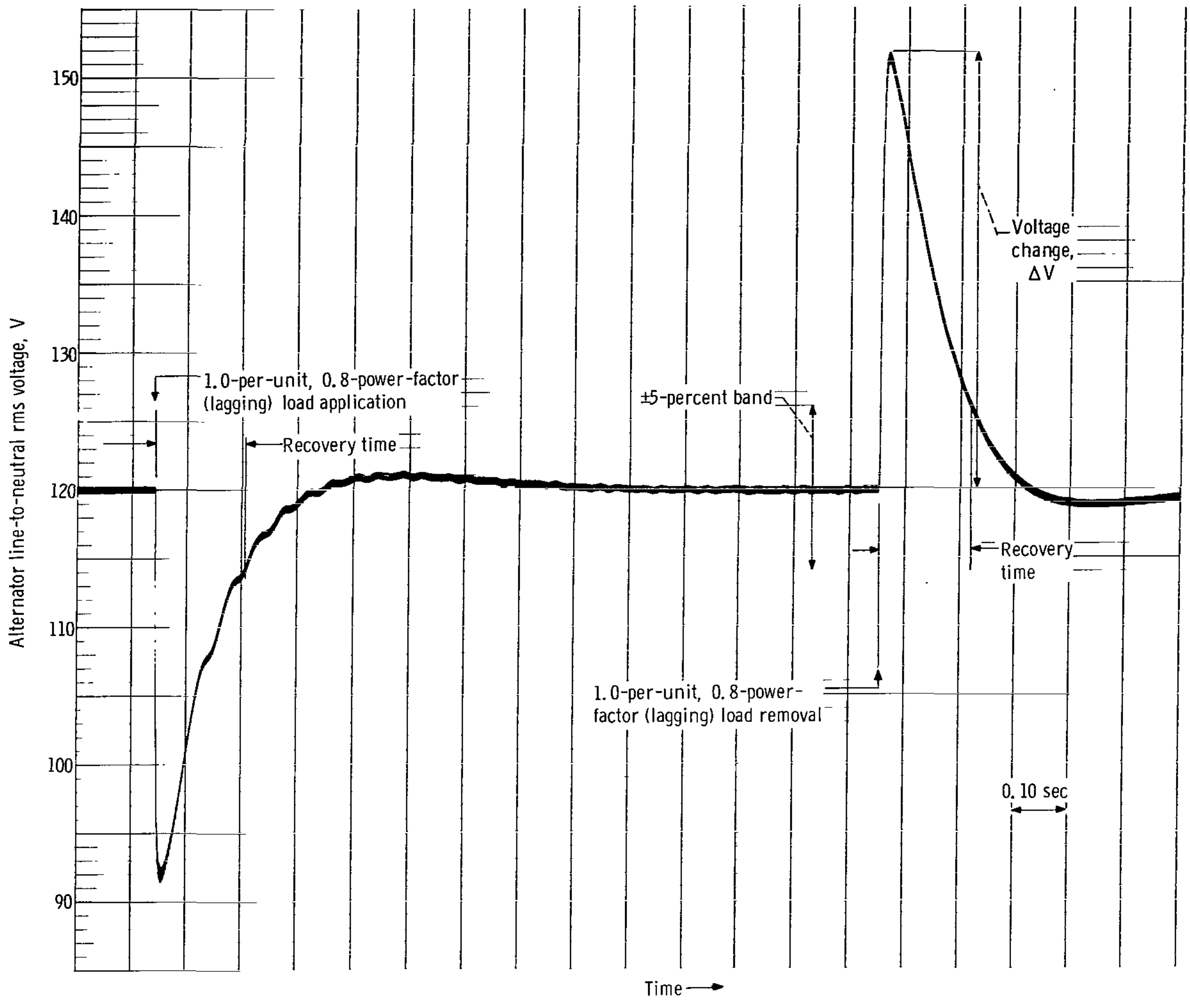


Figure 14. - Voltage transients due to 1.0-per-unit, 0.8-power-factor (lagging) load application and removal.

thus indicating that the VRE tends to flatten the output voltage waveshape. However, as the crest factor is reduced only 0.5 percent at rated load, the effect is negligible.

Amplitude modulation. - Figures 13 and 14 are oscillograph traces of the alternator output voltage with the VRE for unity and 0.8 power factor, respectively. It is apparent that for unity power factor, the output is amplitude modulated with a frequency of modulation of approximately 25 hertz, while at 0.8 power factor, such modulation is negligible.

With the aid of an amplitude modulation meter, values of modulation for several different alternator load conditions were obtained. For 0.8 power factor loads, the modulation was much less than 0.1 percent. The results for unity power factor loads are shown in figure 15. Once again, the data show that the effect of the VRE on the alternator output is negligible.

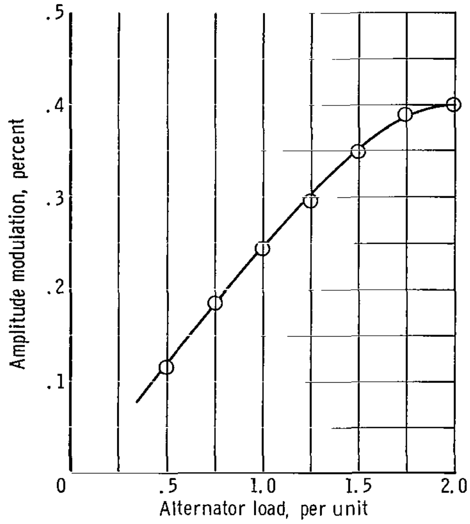


Figure 15. - Brayton cycle alternator and voltage regulator-exciter amplitude modulation as function of alternator load. Power factor = 1.0.

Transient Performance During Step Load Switching

When the voltage departs from its design value because of load application or load removal, the VRE will attempt to restore the voltage to its former value. Typical of the resultant voltage excursions are those shown in figures 13 and 14. The figures show the envelope of the alternator output voltage as a function of time. In both figures, the alternator is initially open-circuited and then step loads of 1 per unit, 1.0 power factor and 1 per unit, 0.8 power factor, respectively, were applied and then removed.

Of particular interest in these voltage transients are the maximum overshoot (or undershoot) and the recovery time. These will now be defined with the aid of figure 14.

$$\% \text{ Overshoot (or \% Undershoot)} = \frac{\Delta V}{120} \times 100$$

Recovery time: the time for the voltage to return to within ±5 percent of 120 volts

For small load application or removal, the voltage never left the ±5 percent band, so that in these cases, by definition, the recovery time is zero.

The overshoot, undershoot, and recovery time were determined from oscillograph traces such as those shown in figures 13 and 14 for several different loads. In all cases the alternator was open-circuited both before load application and after load removal.

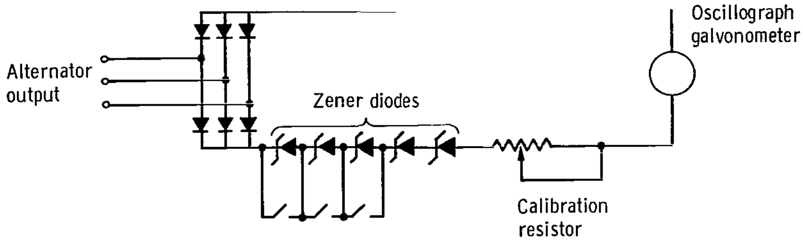


Figure 16. - Circuit used to obtain load switching transients.

To obtain the traces, the circuit shown in figure 16 was employed. The three-phase full-wave rectifier provides a direct current signal proportional to the envelope of the alternating current output. The Zener diodes subtract a constant dc voltage to allow greater amplification of that portion of the trace which is of interest. This circuit has minimum reactance to give fast, accurate transient response.

Each transient was repeated three times, and the results were averaged to give the final values of overshoot, undershoot, and recovery time. These are plotted against the load changes in figures 17 and 18. As the figures show, the maximum overshoot for a 1.0-per-unit load change is less than 30 percent. This occurs for a 0.8 power factor load. For larger power factors, the overshoot is less. The recovery time for load changes of 2 per unit or less and with a power factor of 0.8 or greater, is less than 1/4 second.

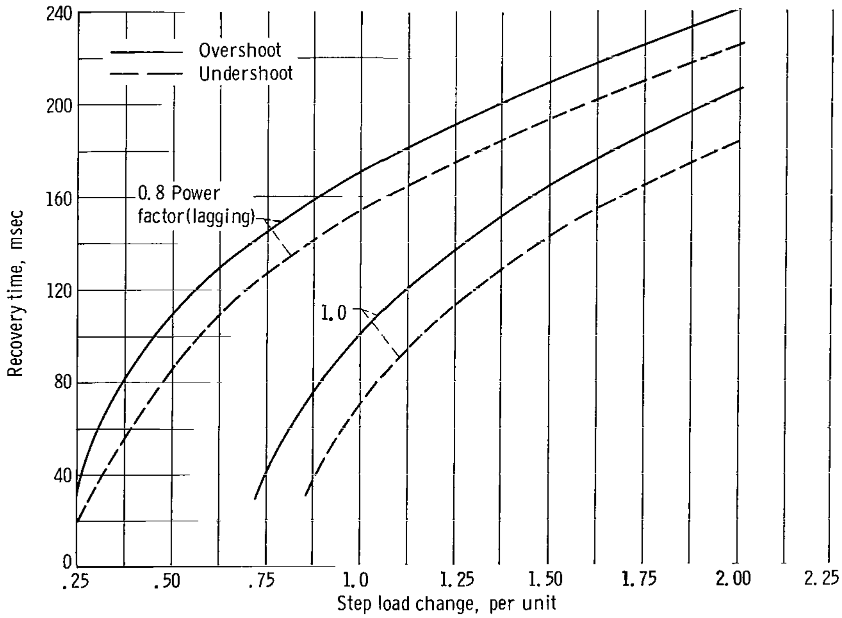


Figure 17. - Brayton cycle alternator and voltage regulator-exciter transient recovery time for step load change.

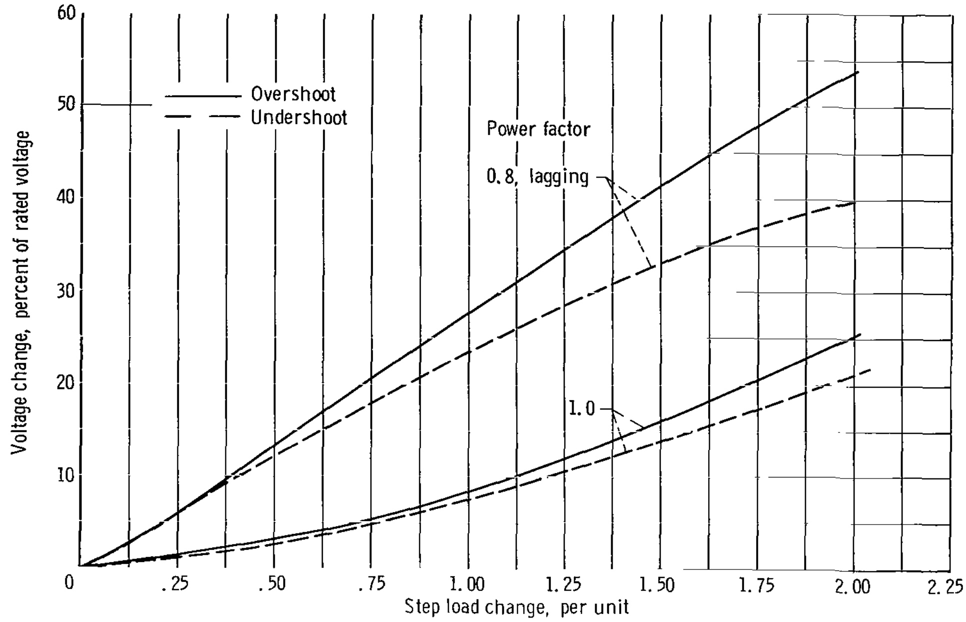


Figure 18. - Brayton cycle alternator and voltage regulator-exciter voltage excursion for step load change.

Voltage Buildup

There are two methods available to initiate voltage buildup with the type of VRE described above. Field flashing is the most dependable and therefore the most commonly used method. It employs an external direct current power supply to furnish field current until the alternator voltage is high enough for the generating system to be self-sustaining. The second method relies on the residual magnetism of the alternator rotor. It is a simpler, more convenient method and requires no external equipment. This is the method which was experimentally investigated.

A measure of the residual magnetism is the residual voltage which is defined as the alternator open-circuit terminal voltage generated by the residual magnetism alone with the rotor spinning at rated speed (12 000 rpm).

If the alternator voltage is to build up without field flashing, then there must be some speed less than rated speed at which (1) the alternator output voltage is nonzero; and (2) the open-loop steady-state gain (G_{OL}) is greater than unity.

G_{OL} is the product of the steady-state alternator gain and the steady-state VRE gain, or with reference to figure 5.

$$G_{OL} = \left[\frac{\begin{matrix}\text{Alternator steady-state} \\ \text{output voltage}\end{matrix}}{\begin{matrix}\text{Alternator steady-state} \\ \text{input current}\end{matrix}}\right]\left[\frac{\begin{matrix}\text{VRE steady-state} \\ \text{output current}\end{matrix}}{\begin{matrix}\text{VRE steady-state} \\ \text{input voltage}\end{matrix}}\right] = \left[\frac{V_{LN}}{I_{F-A}}\right]\left[\frac{I_{F-VRE}}{V_{LN}}\right] = \frac{I_{F-VRE}}{I_{F-A}}$$

G_{OL} is a function of rotor speed, alternator terminal voltage, residual voltage, alternator load, and field resistance. However, data were obtained for no-load and 4-ohm field resistance only. (The field resistance is approximately 4 ohms at the no-load field temperature.)

The residual magnetism generates a nonzero voltage to satisfy requirement (1). It also affects the value of G_{OL} of requirement (2). In general, for low values of V_{LN} ($V_{LN} < 20$ volts), increasing the residual magnetism tends to increase G_{OL}. This means that G_{OL} becomes unity at a lower rotor speed, or, equivalently, voltage buildup occurs at a lower rotor speed.

Data which define the relation between the residual voltage and the "voltage buildup" speed were obtained as follows:

First, the residual magnetism was varied by momentarily energizing the alternator field. Normal field polarity increased the residual magnetism while reverse polarity decreased it. The residual voltage was then measured. Finally, with the alternator at

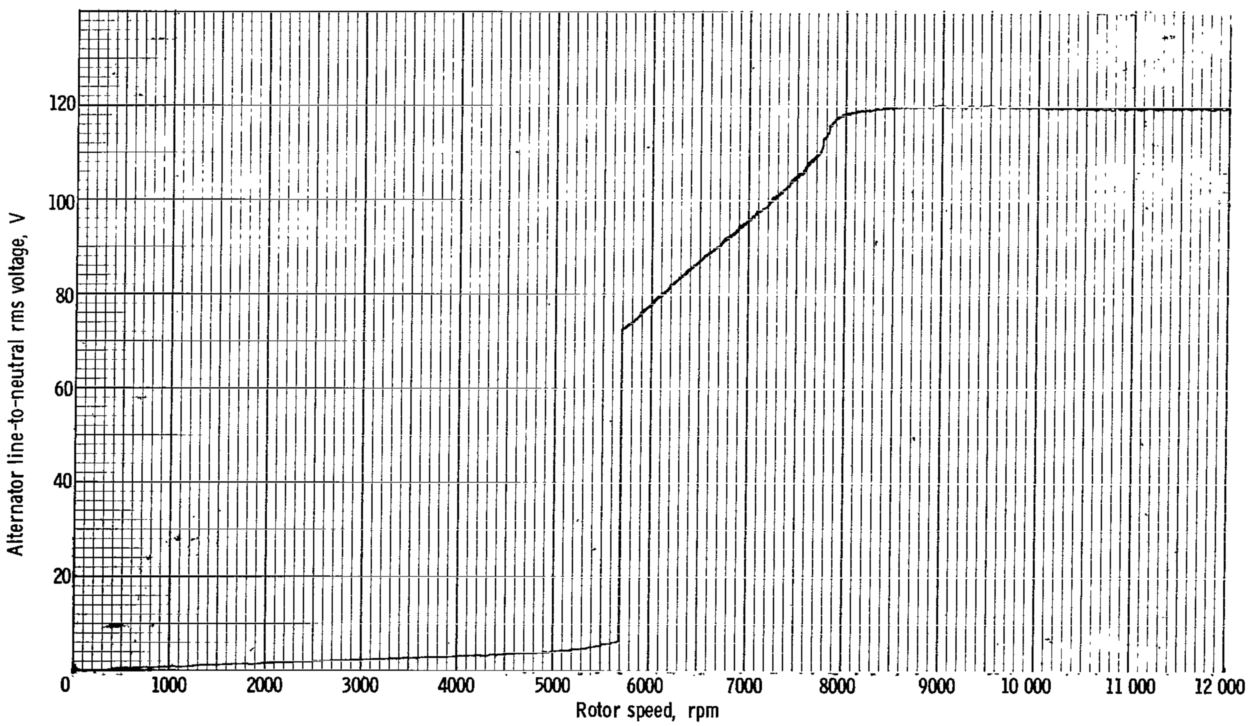


Figure 19. - Alternator voltage buildup against rotor speed for alternator and voltage regulator-exciter. Alternator load, open circuit; residual voltage, 9.38 volts.

no load, a plot of alternator voltage against rotor speed was obtained. The rotor speed was increased very slowly to maintain in effect steady-state conditions.

Typical of the curves obtained is the one shown in figure 19, which is for a residual voltage of 9.38 volts. As the graph shows for this value of residual voltage, the alternator voltage builds up at 5700 rpm (190 Hz). Similar graphs were obtained for other values of residual voltage giving corresponding values of speed.

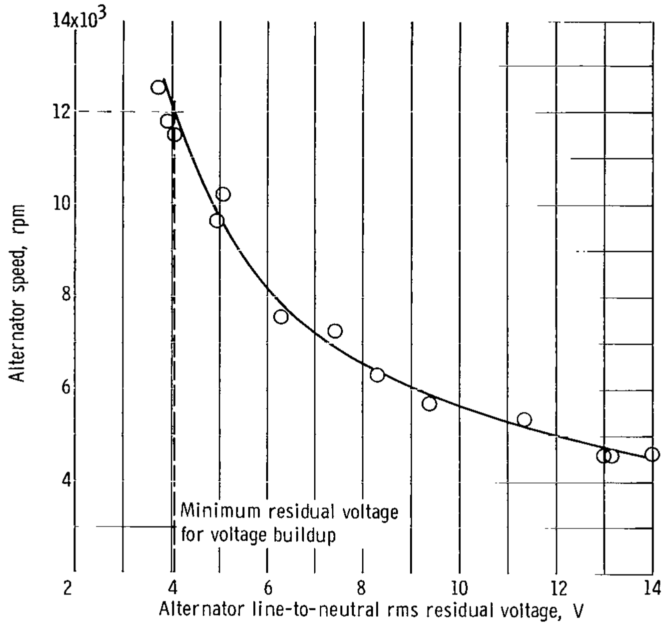


Figure 20. - Voltage buildup speed as function of residual voltage. No load on alternator.

A plot of "voltage-buildup" speed against residual voltage is given in figure 20. The figure shows that with no load on the alternator, voltage buildup will occur at less than 12 000 rpm for values of residual voltage greater than 4.1 volts. Normally, when the alternator is shut down by first removing the load and then opening the field, the residual voltage will be approximately 13 volts. This is considerably more than necessary to achieve voltage buildup at less than rated speed.

SUMMARY OF RESULTS

The ability of the voltage regulator-exciter to supply alternator excitation and to regulate the alternator voltage was evaluated. The VRE performance during transient and startup conditions was determined, and possible adverse effects of the VRE on alternator voltage waveshape and efficiency were assessed. The following experimental results were obtained:

1. The no-load to rated load voltage regulation is less than +0. 2 percent.

2. At rated load the VRE output capacity is 133 percent of that required by the alternator; at no load it is 173 percent.

3. At rated load the efficiency of the alternator and VRE combination is 0. 6 percent less than the efficiency of the alternator alone.

4. VRE power loss is 81. 4 watts at rated alternator load.

5. The effect of the VRE on the alternator output voltage, as measured by the total harmonic distortion, the crest factor, and the amplitude modulation, is negligible.

6. Transient voltage excursions are:

(a) Less than 30 percent of rated voltage on removal of one per unit load

(b) Less than 55 percent of rated voltage on removal of two per unit load

7. The recovery time for a 1 per unit load change is less than 0. 18 seconds.

8. Voltage buildup can be achieved by relying only on the rotor residual magnetism with no load on the alternator for values of residual voltage greater than 4. 1 volts. A typical value of residual voltage is 13 volts.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 25, 1968,
120-27-03-42-22.

APPENDIX - DERIVATION OF AN EXPRESSION FOR MEASURING VOLTAGE REGULATOR-EXCITER POWER LOSS

An expression for average power, which will be convenient for what follows, is

$$P = \mathrm{Re}(\bar{V}\bar{I}^*)$$

Stated in words, average power is equal to the real part of the product of the voltage phasor and the complex conjugate of the current phasor. (The bar denotes phasor quantities, and the asterisk denotes complex conjugates.)

If it is desirable to measure the difference between two quantities, $P_1 - P_2$, where the difference is small compared with both P_1 and P_2, accuracy becomes a problem.

The solution to this problem will be found in the following derivation: Let

$$P_1 = \mathrm{Re}\left(\bar{V}_1\bar{I}_1^*\right)$$

$$P_2 = \mathrm{Re}\left(\bar{V}_2\bar{I}_2^*\right)$$

where

$$\bar{V}_1 \approx \bar{V}_2$$

$$\bar{I}_1 \approx \bar{I}_2$$

$$P_1 - P_2 = \mathrm{Re}\left(\bar{V}_1\bar{I}_1^*\right) - \mathrm{Re}\left(\bar{V}_2\bar{I}_2^*\right) = \mathrm{Re}\left(\bar{V}_1\bar{I}_1^* - \bar{V}_2\bar{I}_2^*\right)$$

$$= \mathrm{Re}\left(\bar{V}_1\bar{I}_1^* - \bar{V}_2\bar{I}_2^* - \bar{V}_2\bar{I}_1^* + \bar{V}_2\bar{I}_1^*\right)$$

$$= \mathrm{Re}\left[\left(\bar{V}_1\bar{I}_1^* - \bar{V}_2\bar{I}_1^*\right) + \left(\bar{V}_2\bar{I}_1^* - \bar{V}_2\bar{I}_2^*\right)\right]$$

$$= \mathrm{Re}\left[\left(\bar{V}_1 - \bar{V}_2\right)\bar{I}_1^*\right] + \mathrm{Re}\left[\bar{V}_2\left(\bar{I}_1^* - \bar{I}_2^*\right)\right]$$

$$= \mathrm{Re}\left[\left(\bar{V}_1 - \bar{V}_2\right)\bar{I}_1^*\right] + \mathrm{Re}\left[\bar{V}_2\left(\bar{I}_1 - \bar{I}_2\right)^*\right]$$

$$= P_A + P_B$$

where

$$P_A = \text{Re}\left[\left(\overline{V}_1 - \overline{V}_2\right)\overline{I}_1^*\right] = (V_1 - V_2)(I_1) \cos \theta_A$$

$$P_B = \text{Re}\left[\overline{V}_2\left(\overline{I}_1 - \overline{I}_2\right)^*\right] = (I_1 - I_2)(V_2) \cos \theta_B$$

θ_A phase angle between $(V_1 - V_2)$ and I_1

θ_B phase angle between $(I_1 - I_2)$ and V_2

If $\overline{V}_1 \approx \overline{V}_2$ and $\overline{I}_1 \approx \overline{I}_2$, then P_A and P_B will be small compared with P_1 and P_2.

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